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The central density of R136 in 30 Doradus *(Research Note)*

Fernando J. Selman[1] and Jorge Melnick[1]

European Southern Observatory, Alonso de Cordova 3107, Santiago
e-mail: fselman@eso.org

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ABSTRACT

The central density ρ_0 of a stellar cluster is an important physical parameter to determine its evolutionary and dynamical state. The degree of mass segregation, or whether the cluster has undergone core collapse both depends on ρ_0. We reanalyze the results of a previous paper that gives the mass density profile of R136 and combine them with both a conservative upper limit for the core parameter and a more uncertain recent measurement. We thus place a lower limit on ρ_0 under reasonable and defensible assumptions about the IMF and its extrapolation to lower masses finding $\rho_0 \geq 1.5 \times 10^4 M_\odot/pc^3$ for the conservative assumptions $a < 0.4$pc for the cluster core parameter. If we use the smaller, but more uncertain value $a = 0.025$pc, the central density estimate becomes larger than $10^7 M_\odot/pc^3$. A mechanism based on the destruction of a large fraction of circumstellar disks is posited to explain the hitherto unexplained increase in reddening presented in that same work.

Key words. star-burst cluster – IMF – core collapse

1. Introduction

Owing to its nearness and extreme nature R136 has not only been a template for other more extreme and distant starburst clusters, but also a good simile of what a typical galactic globular cluster looked soon after its birth. To obtain its physical characteristics in a way firmly rooted in observations has been an important goal as the many studies of this interesting object attest (Melnick 1985; Parker and Garmany 1993; Malumuth and Heap 1994; Brandl et al. 1996; Campbell et al. 1992; Hunter et al. 1995; Hunter et al. 1996; Massey and Hunter 1998; Andersen et al. 2009; Campbell et al. 2012; Sabbi et al. 2012). Selman et al. (1999b, henceforth SMBT) studied the IMF of R136 and provided several of its physically relevant parameters, including the mass density profile of the cluster. Three very important results of that paper were an insight in the age structure of the cluster, the normal nature of its IMF, and the scale free character of the mass density profile between 0.4 and 10 pc.

The cuspy profile and the small core radius has been used to posit a post-core-collapse (PCC) state for this cluster (Campbell et al.1992; but see opposite views by Malumuth and Heap 1994, Brandl et al. 1996, and Mackey and Gilmore 2003). PCC clusters are characterized by a high central density and a density profile that can be modeled by a normal King profile which shows a break and turns into a power-law near the center. High central density means in this context that the relaxation time is short compared with the age of the system. Observations of Galactic globular clusters show that they can be separated into "core-collapsed" and non-core-collapsed depending on whether their photometric profile turns into a power-law near the center (Harris 1996; McLaughlin and van der Marel 2005; Chatterjee et al. 2012 and references therein). The cluster R136 has been claimed to have the characteristics of a PCC cluster: cuspy density profile (Mackey and Gilmore 2003), and a large number of run-away stars (see Fujii et al. (2012) and references therein). Nevertheless, the time scale for core-collapse is too long if we believe the value of $3 \times 10^4 M_\odot/\mathrm{pc}^3$ determined by Mackey and Gillmore (2003). Fujii et al. (2012) invoque the fact that smaller clusters evolve faster to speed up the evolution via hierarchical merging of smaller substructures.

This idea has been backed by the recent work of Sabbi et al. (2012). Using HST optical and NIR data, together with PMS tracks, they claim that R136 is a double cluster currently interacting. They use morphological evidence, and more importantly, age information. They find that the central part of the cluster is very young with ages below 1My, while an overdensity ~5.4 pc to the northeast of the center is closer to 2.5 My. Similar ages were found in SMBT, but using fits to the Geneva tracks in the upper part of the HR diagram. That similar age structure is found using these two sets of tracks give credibility to both of these results.

Such a complex age structure is quite a complication when modeling to convert magnitudes and colours into masses. If the average age of the stellar population depends on radius this will result in systematic errors in our estimates of physical parameters unless variable ages are allowed in the modeling. Most work on R136 so far assume simple stellar populations. The only work that we are aware off that does not is SMBT, which also considers variable reddening determined in a star-by-star basis, and does a full completeness analysis, fundamental when working in the optical bands.

Using ground-based observations in combination with the HST work of Hunter et al. (1995, 1996) SMBT determined the density profile of the cluster showing that is well represented by a single power-law between 0.4 - 10 pc, giving explicit expressions. Although a lower limit to the central density of the cluster can be derived from those numbers, it was not given explicitly in the paper. In this research note we give the explicit results. If we use the same core parameter used by Mackey and Gilmore (2003) we find a striking similarity between our result and that

of those authors. Furthermore, using the recent estimates of the core parameter by Campbell et al. (2012) we find that the central density is considerably larger than the previous estimate, making core-collapse a virtual certainty for this cluster, or an indication that the latter estimate of the core parameter is really bogus.

2. Radial profile, central density, and total mass in R136

SMBT give the following relation for the stellar number density normalized to 1 pc, derived counting stars with masses between $10M_\odot < M < 40M_\odot$:

$$\rho_n(r) \;=\; 9.8\,\frac{\text{stars}}{\text{pc}^3}\left(\frac{1\text{pc}}{r}\right)^{2.85}, \tag{1}$$

where r is the distance to the cluster center in parsecs. As previously noted, a large effort was made by SMBT to correct for incompleteness, and, although the work was based on optical data, Equation (1) should not be affected by differential reddening and should be complete in the specified mass range.

A form very much used to parametrize the stellar density of a star cluster was given by Elson, Fall, & Freeman (1987):

$$\rho(r) \;=\; \rho_0 \times \frac{1}{\left(1+\left(\frac{r}{a}\right)^2\right)^{\frac{\gamma+1}{2}}}, \tag{2}$$

where a is the core parameter[1], and ρ_0 is the central density. Given a core parameter, then and only then we can calculate ρ_0. If we only have valid measurements in the power law region, where $r >> a$, we can only obtain a lower limit to ρ_0. Thus, the challenge in the determination of the central density is really a challenge in the determination of the core parameter. There are basically two methods to determine this parameter: fits to star counts, and fits to the integrated light profile. Brandl et al. (1996) cautions that the determination of the core parameter using surface brightness profiles is not reliable, as the light can be dominated by a few very bright stars (as is indeed the case near the center of R136), and mimic a power-law cusp. A similar caveat can be found in Mackey and Gilmore (2003).

We can write the results for the stellar volume density found in SMBT using the Elson, Fall, & Freeman (1987) form for an arbitrary value of a but fitting the SMBT power law data:

$$\rho_n(r) \;=\; 9.8\frac{\text{stars}}{\text{pc}^3}\times\left(\frac{1pc}{a}\right)^{1.85+1}\frac{1}{\left(1+\left(\frac{r}{a}\right)^2\right)^{\frac{1.85+1}{2}}}, \tag{3}$$

of slope $\gamma = 1.85$, with a clear power-law behaviour without signs of a core between 0.4 - 10 pc. Figure 1 reproduces Figure 13 from SMBT which gives a profile totally determined counting stars in *mass* bins.

Using the value $a = 0.4$ pc as an upper limit we can write the previous result as,

$$\rho_n(r) \;\geq\; 133\frac{\text{stars}}{\text{pc}^3}\frac{1}{\left(1+\left(\frac{r}{a}\right)^2\right)^{\frac{1.85+1}{2}}}. \tag{4}$$

[1] The core parameter in the Elson, Fall and Freeman form is related to the King profile core radius by $r_c = a\sqrt{2^{2/\gamma}-1}$. Note that this formula is incorrectly quoted in Campbell et al. (2012), but correctly given in Mackey and Gilmore (2003).

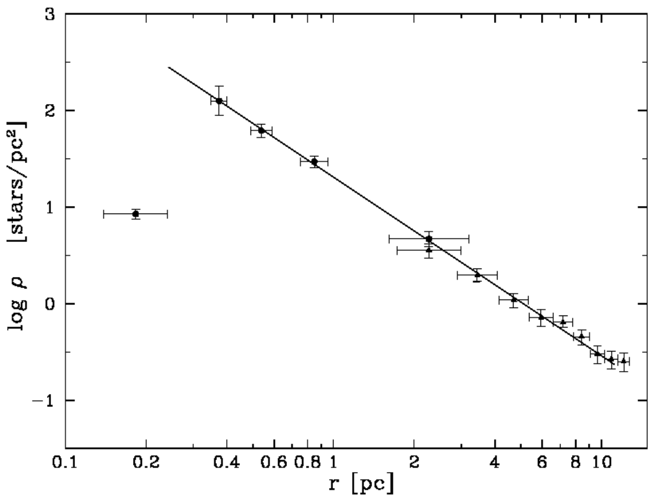

Fig. 1. Radial density profile for the stars with $10M_\odot < M < 40M_\odot$. For the innermost bins we have calculated the points using the Hunter et al. (1995) data following the procedure described in the text. The line is a power law with exponent -1.85. Reproduced with permission from SMBT.

This expression is valid for stars with M in the range $10M_\odot < M < 40M_\odot$. To convert this number density profile to a mass profile we need the spectrum of stellar masses to extrapolate the density from the given mass range to the full mass range. We choose to use the spectrum of masses at birth, that is the IMF, instead of the present-day mass function, although it does not make much of a difference given the young age of the central parts of R136. At 1.2 My the most massive stars have loss less than 4% of their mass. The lowest mass for which an IMF has been given for R136 so far is $1M_\odot$ (Andersen et al. 2009). These authors found consistency with Salpeter slope down to this mass limit. We use this result as a check that the IMF does not show a break down to this mass limit but use the SMBT IMF slope extrapolated down to this mass, as it was determined in a very rigorous and self-consisten way. We thus use a Kroupa IMF (Kroupa 2002) modified in the high mass range to have the slope determined in SMBT ($\Gamma = 1.17$),

$$\xi(m) \;=\; \begin{cases} \left(\frac{m}{0.08}\right)^{-0.3} & 0.01 <= m < 0.08 \\ \left(\frac{m}{0.08}\right)^{-1.3} & 0.08 <= m < 0.5 \\ \left(\frac{0.5}{0.08}\right)^{-1.3}\times\left(\frac{m}{0.5}\right)^{-2.17} & 0.5 <= m < 120 \end{cases} \tag{5}$$

With this IMF the fraction of stars with masses between $10M_\odot < M < 40M_\odot$ is 0.3967%. The fraction in the mass range $1M_\odot < M < 120M_\odot$ is 7.286%, and the average mass is $3.85M_\odot$. Thus, if we choose to integrate only down to $1M_\odot$, we estimate the central mass density limit,

$$\rho_0 \;\geq\; 9.4\times 10^3\,\frac{M_\odot}{\text{pc}^3}. \tag{6}$$

The result in Equation 6 has been derived almost directly from observations. There are modeling uncertainties, but no extrapolations. To extend the result to even lower masses were the mass function has not been determined observationally is somewhat risky. Depending on the actual dynamical state of the cluster we could have the effects of mass segregation invalidating the

result. The mass density profile we obtain with this extrapolation of the IMF to the full $0.01M_{\odot} < M < 120M_{\odot}$ range where the average mass is $0.46M_{\odot}$ is given by,

$$\rho(r) \approx 1.5 \times 10^4 \frac{M_{\odot}}{\mathrm{pc}^3} \frac{1}{\left(1 + \left(\frac{r}{a}\right)^2\right)^{\frac{1.85+1}{2}}}, \tag{7}$$

Mackey and Gilmore (2003) determine an upper limit to the core parameter of $a < 0.32$ pc. With this value we can estimate a lower limit to the central density of $2.8 \times 10^4 M_{\odot}/pc^3$, in excellent agreement with the value of $3 \times 10^4 M_{\odot}/pc^3$ given by those authors.

These numbers can also be used to determine a total mass. The complication here is that the slope of the density profile results in an ever increasing total mass as one go to larger radii. Here we choose to cut the integration at a radius of 10 pc, distance at which the star counts become noisier due to a number of substructures present at these distances. The same slope value that diverges for large radius ensure convergence when integrating from the center. Thus, we will give our estimates of the mass of the cluster as a range where the lower total mass limit is given by the upper limit of the core parameter, and the upper total mass limit is given for a power-law all the way to the center. With these assumption we can then write, using

$$M_{tot} = 4\pi a^3 \rho_0 \int_0^{R/a} \frac{u^2 du}{(1+u^2)^{\frac{\gamma+1}{2}}} = 4\pi a^3 \rho_0 F\left(\frac{R}{a}\right), \tag{8}$$

where we have defined

$$F\left(\frac{R}{a}\right) = \int_0^{R/a} \frac{u^2 du}{(1+u^2)^{\frac{\gamma+1}{2}}} \tag{9}$$

and in what follow we integrate numerically. We note that for $\gamma > 2$ the integral converges in the limit $R/a \to \infty$. For $\gamma = 2$ it diverges logarithmically.

With these definitions the constraint to the total mass becomes,

$$4\pi a^3 \rho_0 F\left(\frac{R}{a}\right) < M_{tot} < 4\pi a^3 \rho_0 F\left(\frac{R}{a}\right) \frac{\frac{1}{2-\gamma}\left(\frac{R}{a}\right)^{2-\gamma}}{F\left(\frac{R}{a}\right)} \tag{10}$$

and for R136 using $a < 0.4$ pc,

$$4.6 \times 10^4 M_{\odot} < M_{tot} < 1.3 \times 10^5 M_{\odot}, \tag{11}$$

or in terms of total number of stars N_{tot},

$$10^5 < N_{tot} < 2.8 \times 10^5. \tag{12}$$

3. Discussion

As noted in the previous section the estimate of the central mass density depends very strongly on the limits that we put on the core parameter. Because it was determined by star counts we feel that the limit given in SMBT is a very conservative one. Several other authors have placed much more stringent constraint by analyzing the light profile. One of the latest such studies, and reaching similar conclusions as other studies that use the surface brightness method is that of Campbell et al. (2012). They used the multiconjugate adaptive optics instrument (MAD) at ESO's Melipal 8-m telescope to perform star counts and surface photometry in H and K, on frames with typical Strehl ratios in K of 15 - 25%. Although in the infrared there is little leverage for disentangling masses and ages, it is less affected by reddening so with proper care a good estimate of the radial profile can be obtained in the case of a *simple stellar population.* Their magnitude limit corresponds to approximately $5M_{\odot}$. Within approximately $r < 2pc$ they use the light profile integrated in annuli, while for $r > 0.7pc$ they use star counts. They merge the two profiles into a single one using the area of overlap to normalize the two sets. They find $\gamma = -1.6 \pm 0.1$, and $a = 0.025pc$. Because of the presence of radially dependent stellar populations with multiple ages we will only use in what follow only their value for the core radius, and for the slope we will use the value determined in SMBT where allowance was made for multiple epochs of star formation.

The issues complicating the determination of the core parameter using integrated light profiles are not addressed at all by Campbell et al. (2012), but are of fundamental importance in this kind of studies. A look at their Figure 20 shows that the power-law slope is virtually the same for the segment derived with star counts and the segment derived by the surface brightness fit. This might indicate that the surface brightness is a good proxy for mass surface density. Nevertheless, we must point out that the very bright central sources could give a similar signal due to scattering of light in the optical elements of the instrument. It has been known for a long time that the profile of a stellar image contains a kernel and a power'law part of index ~ -2 (King 1971). This index is suspiciously close to the -1.6 index determined with MAD.

Taken at face value the results of Campbell et al. of $a = 0.025$ pc, imply a central density of

$$\rho_0 \geq 4.0 \times 10^7 \frac{M_{\odot}}{\mathrm{pc}^3}, \tag{13}$$

and

$$\begin{aligned} 7.5 \times 10^4 M_{\odot} &< M_{tot} < 1.3 \times 10^5 M_{\odot}, \\ 1.6 \times 10^5 &< N_{tot} < 2.8 \times 10^5, \end{aligned} \tag{14}$$

which are much larger than any other estimates of the R136 central density, total mass, and total number of stars.

So is R136 a PCC cluster? If we take the MAD data at face value the cluster must be in a PCC state since the relaxation time for a cluster with such central density is only $\sim 8 \times 10^3$y, and the time to core-collapse is approximately 15 times this value (using Binney and Tremaine (1987), as presented in Equation 8 by Mackey and Gilmore (2003)), or $\sim 1 \times 10^5$y, considerably below to the current estimate of 10^6y for the age of the cluster.

Two other subtleties related to relaxation and core-collapse must be pointed out. First, the identification of "core-collapsed" clusters in the galaxy rests in the identification of a *break* in the inner part of the light profile. R136 when properly studied, that is by star counts, shows a scale-free distribution from 10 pc all the way down to at least 0.4 pc. Second, the relaxation times used in the literature assume a single mass component while for this very young cluster we have a spectrum of masses spanning at least three orders of magnitude. In such a case the relaxation time is diminished by the ratio of the lowest mass to the highest mass star. We do not dwelve deeper in this subject as the physics of core-collapse is beyond the scope of this research note.

Given that the central density of the cluster could be as high as that implied in Equation 13 we would like to point out another interesting, albeit more speculative, possibility. Selman et. al. (1999b), the first paper of the series and dedicated in part to the study of the reddening distribution in R136, found the puzzling

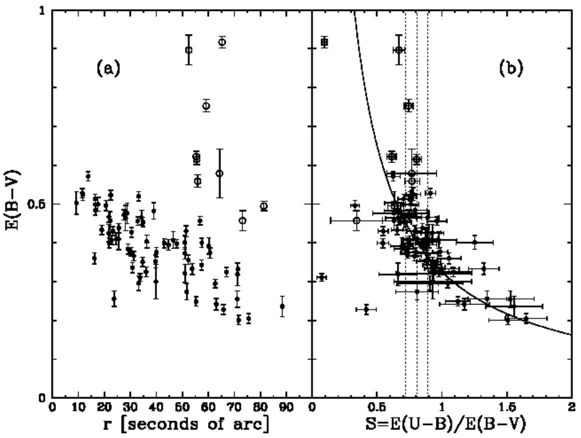

Fig. 2. (a) Radial profile of colour excess, as determined in Selman et al (1999). (b) Colour excess versus selective extinction parameter S. Reproduced with permission from Selman et al. (1999).

results of an increasing trend in reddening toward the center of the cluster. Their Figure 6(a), reproduced here as Figure 2 shows clearly that trend. The figure show that in the inner regions most of the stars show a somewhat limited amunt of variable extinction which increases toward the center. In the outer parts a large fraction of the stars follow the same trend, while another group, probably associated with the nebulosity that surrounds the cluster, show a much larger variation of extinction. The amount of dust associated with the inner component was estimated at 30-$60 M_{\odot}$ within 15 pc, and its origin was a mystery. In a recent series of papers Olczak et al. (2012, and references therein) have proposed, based upon numerical simulations, that in an ambient as dense as the core of the Arches cluster encounters can destroy up to 1/3 of the circumstellar disks. If Equation 13 represents the physical state of the cluster then the disk destruction process might be responsible, at least in part, for the inner extinction that we have measured. A safe upper limit to the average disc mass is 0.1 $M_{\odot}$. Assuming the typical gas-to-dust ratio of 100, a disc provides a maximum of $1.0 \times 10^{-3} M_{\odot}$ of dust on average; the observed amount of dust requires at least a few 10^4, entirely depleted discs (Olczak private comm). If we assume that only stars with masses above $0.3 M_{\odot}$ can hold such disks, and using that the fraction of stars with such masses is approximately 27%, the total number of stars with masses above $0.3 M_{\odot}$ implied by Equation 14 is 4.3×10^4. Thus, a considerable fraction of the disk population must be destroyed, and rather rapidly.

4. Conclusions

In this research note we estimate a conservative limit to the central mass density of R136 of $1.5 \times 10^4 M_{\odot}/\mathrm{pc}^3$ for $a < 0.4$pc. From this we estimate that the total mass of the cluster enclosed within 10 pc must be in the range

$$4.6 \times 10^4 M_{\odot} < M_{tot} < 1.3 \times 10^5 M_{\odot},$$

or in terms of total number of stars N_{tot},

$$10^5 < N_{tot} < 2.8 \times 10^5.$$

In this case the observed scale free profile must be in place at the moment of formation as relaxation and core collapse have not had time to act in this young object.

On the other hand, if we take the recent estimate of the core parameter at face value (Campbell et al. 2012), we get the much more extreme set of constraints

$$\rho_0 \geq 4.0 \times 10^7,$$

and

$$7.5 \times 10^4 M_{\odot} < M_{tot} < 1.3 \times 10^5 M_{\odot},$$

and core-collapse becomes a certainty.

Such large central density can have other effects. For example, the reddening distribution, observed by SMBT to increase toward the inner parts of the cluster, is posited in this research note to come from the destruction of a large fraction of the circumstellar disks in R136, establishing their existence in this starburst cluster.

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